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Mathematical model for gas–liquid two-phase flow and biodegradation of a low concentration volatile organic compound (VOC) in a trickling biofilter

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Abstract

A theoretical model is established for predicting the biodegradation of a low concentration volatile organic compound (VOC) in a trickling biofilter. To facilitate the analysis, the packed bed is simplified to a series of straight capillary tubes covered by the biofilm in which the liquid film flow on the surface of biofilm and the gas core flow in the center of tube. The theoretical formulas to calculate liquid film thickness in the capillary tube are obtained by simultaneously solving a set of hydrodynamic equations representing the momentum transport behaviors of the gas–liquid two-phase flow under co-current flow and counter-current flow. Subsequently, the mass transport equations are respectively established for the gas core, liquid film, and biofilm with considering the mass transport resistance in the liquid film and biofilm, the biochemical reaction in the biofilm, and the limitation of oxygen to biochemical reaction. Meanwhile, the surface area of mass transport in the capillary tube is modified by introducing the active biofilm surface area, namely the specific wetted surface area available for biofilm formation. The predicted purification efficiencies of VOC waste gas are found to be in good agreement with the experimental data for the trickling biofilters packed with ∅8 mm, ∅18 mm, and ∅25 mm ceramic spheres under the gas–liquid co-current flow mode and counter-current flow mode. It has been revealed that for a fixed inlet concentration of toluene, the purification efficiency of VOC waste gas decreases with the increase in the gas and liquid flow rate, and increases with the increase in the specific area of packed materials and the height of packed bed. Additionally, it is found that there is an optimal porosity of packed bed corresponding to the maximal purification efficiency.

Keywords: Trickling biofilter; Capillary tube model; Specific wetted surface area of biofilm; Purification efficiency

1. Introduction

In recent years, numerous industrial processes, such as organic chemistry industry, coal industry, rubber regeneration and paint spraying, etc., emit the low concentration volatile organic compounds (VOCs) and the stench gas, which has seriously polluted the atmospheric environment of the local regions. Since the recovery of low concentration VOCs is valueless and its treatment is very difficult and expensive with traditional physical and chemical treatment technologies, the biological treatment technology of VOCs has been more and more extensively applied in the industrial fields because of the high purification efficiency, cost-effectiveness, and environmentally friendliness, etc. The conventional biological reactors for VOCs treatment include biofilters, trickling biofilters, and bioscrubbing filters. It has been proved that trickling biofilters is superior to biofilters when accurate controls of the environmental conditions or higher pollutant elimination rate are required [1]. Besides, trickling biofilters are more recent than biofilters, and have not yet been fully deployed in industrial applications, but the prospective future applications are promising [2]. At present, many researchers have focused

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Nomenclature

A_T	cross-sectional area of the trickling biofilter column, m^2
a	specific surface area of packed material, m^{-1}
a_l	specific active biofilm surface area of trickling biofilter, m^{-1}
C_{bO}	concentration of oxygen in biofilm, g/m^3
C_{bT}	concentration of pollutant in biofilm, g/m^3
C_{gO}	concentration of oxygen in gas phase, g/m^3
C_{gT}	concentration of pollutant in gas phase, g/m^3
C_{lO}	concentration of oxygen in liquid film, g/m^3
C_{lT}	concentration of pollutant in liquid film, g/m^3
D_{bO}	diffusion coefficient of oxygen in biofilm, m^2/s
D_{bT}	diffusion coefficient of pollutant in biofilm, m^2/s
D_{lO}	diffusion coefficient of oxygen in liquid film, m^2/s
D_{lT}	diffusion coefficient of pollutant in liquid film, m^2/s
D_p	diameter of ceramic spheres, m
D_T	diameter of trickling biofilter, m
g	acceleration of gravity, $m\ s^{-2}$
h	height of packed bed, m
K_{IT}	self-inhibition kinetic constant for biodegradation of pollutant, g/m^3
K_O	kinetic constant for biodegradation of oxygen, g/m^3
K_T	kinetic constant for biodegradation of pollutant, g/m^3
m	Henry's constant
n_c	number of capillary tubes
Pe	Peclet number
p_c	capillary pressure, Pa
p	static pressure of gas and liquid in capillary tube, Pa
Q	volume flow rates in trickling biofilter, m^3/h
q	volume flow rates in capillary tube, m^3/s
r_b	radius at the interface of biofilm and liquid film in capillary tube, m
r_l	radius at the interface of gas–liquid in the capillary tube, m
r_s	radius of the capillary tube, m
u	velocity in the capillary tube, m/s
Y_T	dry density of biofilm, kg/m^3
Y_T	yield coefficient of a culture on pollutant

Greek symbols

β	dimensionless number, $\beta_i = X_V \mu_{max} r_S^2 / (Y_T D_{bi} C_{gi,in})$, $i = T, O$
ε	porosity of packed bed in the trickling biofilter
η	purification efficiency of the trickling biofilter
μ	dynamic viscosity, $N\ S/m^2$
μ_{max}	maximum specific growth rate of microorganism, h^{-1}
ρ	density, kg/m^3
σ_l	liquid surface tension, N/m
σ_p	surface tension of packing material, N/m
ξ	correction factor

Superscript

*	dimensionless number

Subscripts

b	biofilm
g	gas phase
in	inlet of the trickling biofilter
l	liquid film

on understanding biofiltration process through theoretical models [3–6]. The first and simple model by Ottengraf and van den Oever [3] described kinetics of the elimination processes. Hodge and Devinny [4] proposed a biofiltration model to simulate the basic transport and biological processes of ethanol reduction and subsequent CO_2 formation in columns containing compost, granular activated carbon, or a mixture of compost and diatomaceous earth. Deshusses et al. [5] established a novel diffusion reaction model for the determination of both the steady-state and transient-state behavior of biofilters for waste air biotreatment.

However, the theoretical research work on the trickling biofilters is limited, most of which take no account of the mass transport resistance in the liquid film over the porous material of the packed bed. Baltzis et al. [7,8] developed a transient model and steady model. In the model, general mixing, oxygen limitation aspects, multi-component adsorption phenomena, Monod- and Andrews-type kinetics with interference between the components were considered with respect to not only single components biodegradation but also multi-component biodegradation. The model accounted of the absorption of pollutant at the gas–liquid interface with Henry's law but neglected the mass transport resistance in the liquid film.

A few models involve the effect of mass transport resistance in the liquid film on the biodegradation of pollutant. Among these models, Sun et al. [9] theoretically studied the axial dispersion, convection film mass-transfer, and biodegradation coupled with deactivation of the TCE-degrading enzyme. Mirpuri et al. [10] developed a predictive model to the degradation of toluene in a flat-plate vapor phase bioreactor (VPBR). The VPBR model incorporated kinetic, stoichiometric, injury, and irreversible loss coefficients from suspended culture studies for the toluene degradation by P. Putida 54G and measured values of Henry's law constant and boundary layer thickness at the gas–liquid and liquid–biofilm interface. Alonso et al. [11] established a model by considering a two-phase system,